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Use of Swarm data to study the core surface magnetic field

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Summary

ESA's Swarm satellite trio, designed to deliver the best ever survey of the Earth's magnetic field was launched on 22nd November 2013. The mission is now providing high quality magnetic data suitable for probing the Earth's core. Here, we illustrate this by presenting a preliminary internal field model derived from Swarm data. Our results were obtained via an update of the CHAOS series of geomagnetic field models to include the first 8 months of quiet time, night side, Swarm vector field magnetometer data, along with recent ground observatory monthly means. The new model spans more than 15 years between 1999 and 2014, using a 6th order spline representation with 0.5 yr knot spacing and imposed temporal regularization.

We are able consistently fit data from 6 different satellites: Ørsted, CHAMP, SAC-C and the three Swarm satellites. We also find that the new model (CHAOS-4plus) provides a good description of observatory secular variation, capturing rapid field evolution events during the past decade. Stable images of the core field and secular variation at the core surface are obtained. Further work is now needed to take explicit advantage of the Swarm constellation.

CHAOS-4plus models can be downloaded from http://www.spacecenter.dk/files/magnetic-models/CHAOS-4.

Swarm satellite constellation

Fig. 1: Artist's view of the 3 Swarm satellites (credit: ESA).

- ESA Earth explorer mission
- Successfully launched on 22nd November, 2013
- Three identical satellites each weighing 473 kg and 9.1 m long (including a 4m deployable boom)
- Carrying high precision vector and scalar magnetometers plus star cameras, mounted on booms
- Two satellites flying close-by (approx. 150 km apart) at a relatively low altitude ~ 470 km, to allow estimation of East-West field gradient
- Third satellite is flying higher ~ 520 km, and drifting at a different rate in local time, allowing space and time field variations to be distinguished
- Constellation still evolving, with satellites slowly descending and the higher satellite drifting to a different local time
- Efforts to improve the calibration of the magnetic field data are ongoing
- Looking forward to a long (approx. 10 year) mission due to the relatively low solar activity

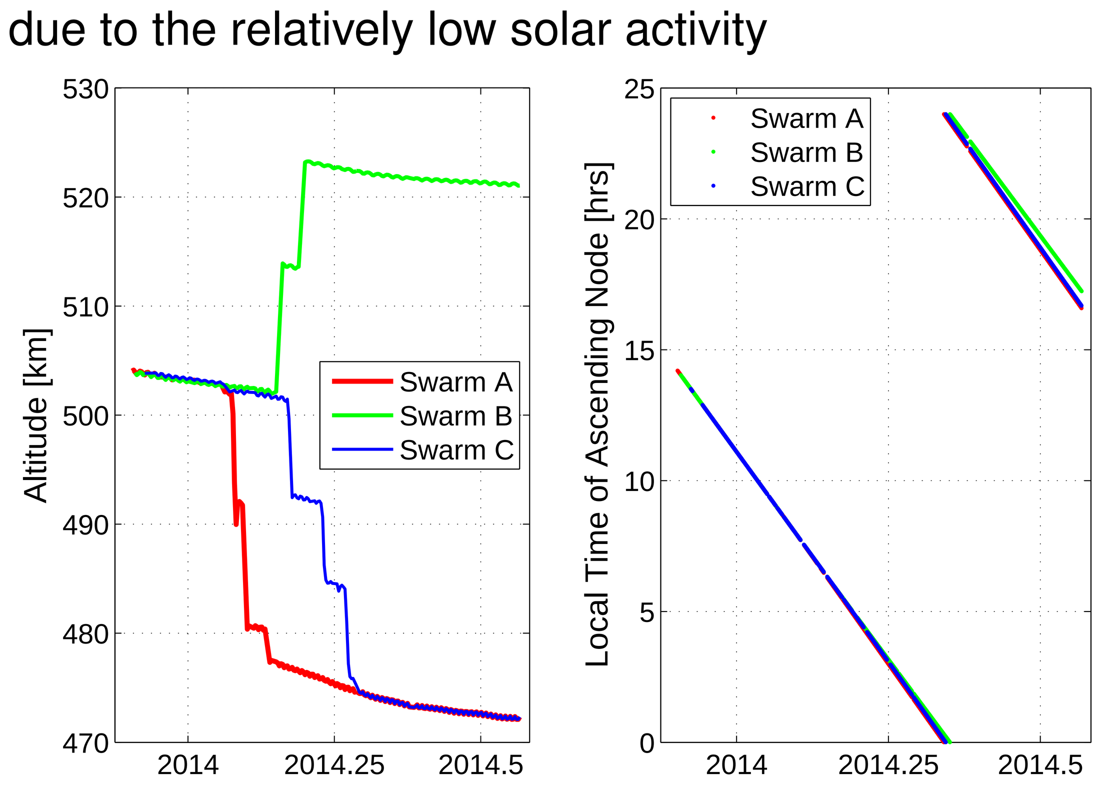

Fig. 2: Daily means of altitudes (left) and local times (right) of the three Swarm satellites showing constellation's development.

Satellite data

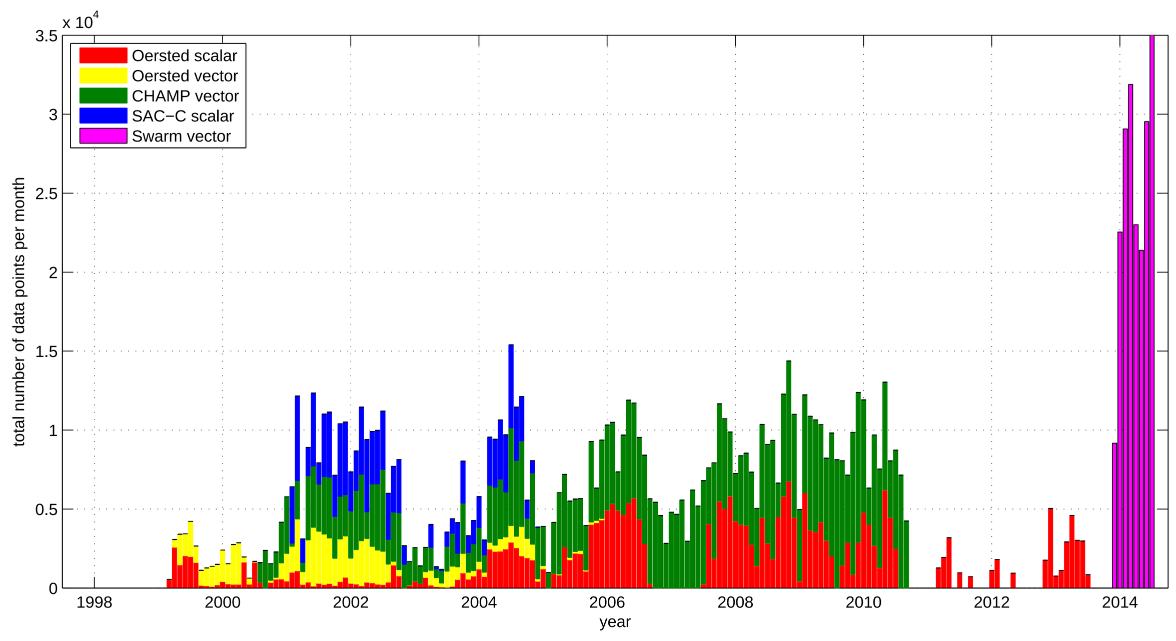

Fig. 3: Number of magnetic data per month used from six different satellites.

- Same data set used for the CHAOS-4 field model (Olsen et al., 2014) plus Swarm data
- Swarm VFM data: release 0302 where possible, otherwise 0301, up until 22nd July 2014
- Night side, 'quiet-time' data selection criteria used as for CHAOS-4, but accepted Swarm data when sun was up to 30 deg above the horizon

Ground magnetic observatory data

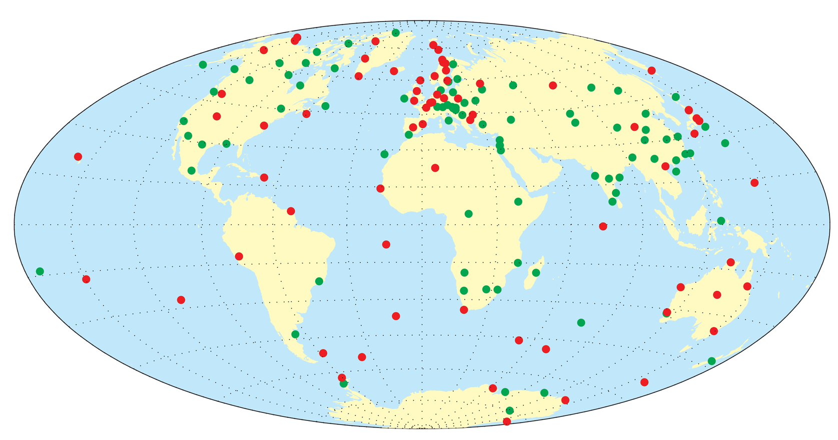

Fig. 4: Locations of ground magnetic observatories used in this study. Those providing data in 2014 are shown in red.

Field modelling methodology

- **Potential field approach:** $\mathbf{B} = -\nabla V,\ V = V^{\text{int}} + V^{\text{ext}}$
- The internal part takes the form

$$V^{\text{int}} = a \sum_{n=1}^{N_{\text{int}}} \sum_{m=0}^{n} \left(g_n^m \cos m\phi + h_n^m \sin m\phi\right) \left(\frac{a}{r}\right)^{n+1} P_n^m(\cos\theta)$$

- And internal coefficients are further expanded as

$$g_n^m(t) = \sum_l g_{n,l}^m \cdot M_l(t) \quad \text{for } n = 1-20$$
$$= g_n^m(t_0) \quad \text{(const.)} \quad \text{for } n = 21-80$$

where $M_l(t)$ are order 6 B-splines with 0.5 yr spacing.

- Model estimation is via **regularized, robust, non-linear least squares** minimizing

$$\mathbf{e}^T \underline{\underline{C}}^{-1}\mathbf{e} + \lambda_3 \mathbf{m}^T \underline{\underline{\Lambda}}_3 \mathbf{m} + \lambda_2 \mathbf{m}^T \underline{\underline{\Lambda}}_2 \mathbf{m}$$

- $\underline{\underline{\Lambda}}_3$ penalizes the model 3rd time derivative
- $\underline{\underline{\Lambda}}_2$ penalizes the model 2nd time derivative, but only at the endpoints

Fit to ground observatory data

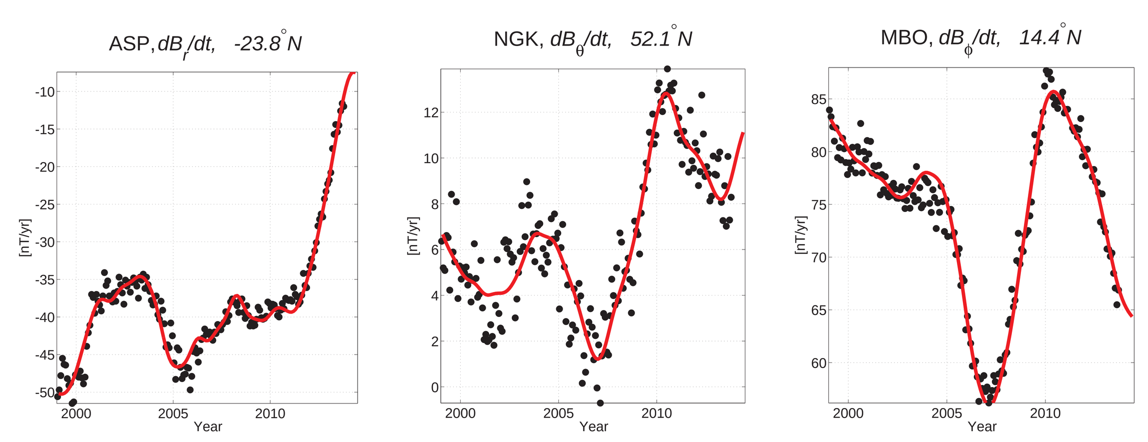

Fig. 5: Annual differences of revised observatory monthly means **(black dots)** compared to the SV prediction from the latest CHAOS-4plus model **(red line)**. ASP=Alice Springs, Australia, NGK= Niemegk, Germany; MBO=M'Bour, Senegal.

Fit to Swarm data: analysis of residuals

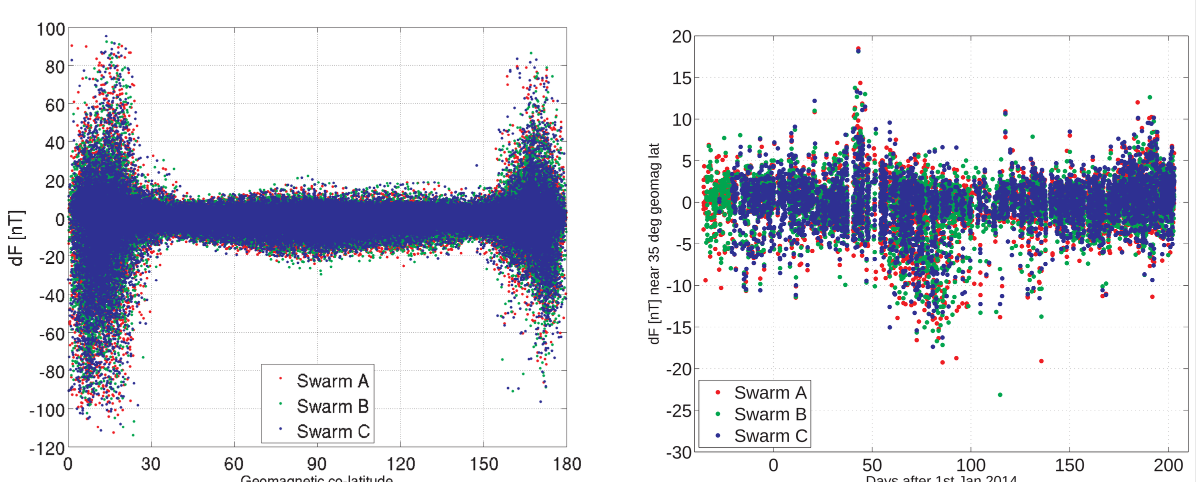

Fig. 6: Total field residuals dF between Swarm A, B, C and the latest CHAOS-4plus model. Above left: Versus geomag. colat.; Above right: Versus time, at 35^o geomag. lat., where the ring current disturbance is $\perp$ to the main field.

Results: Core field evolution in the Swarm era

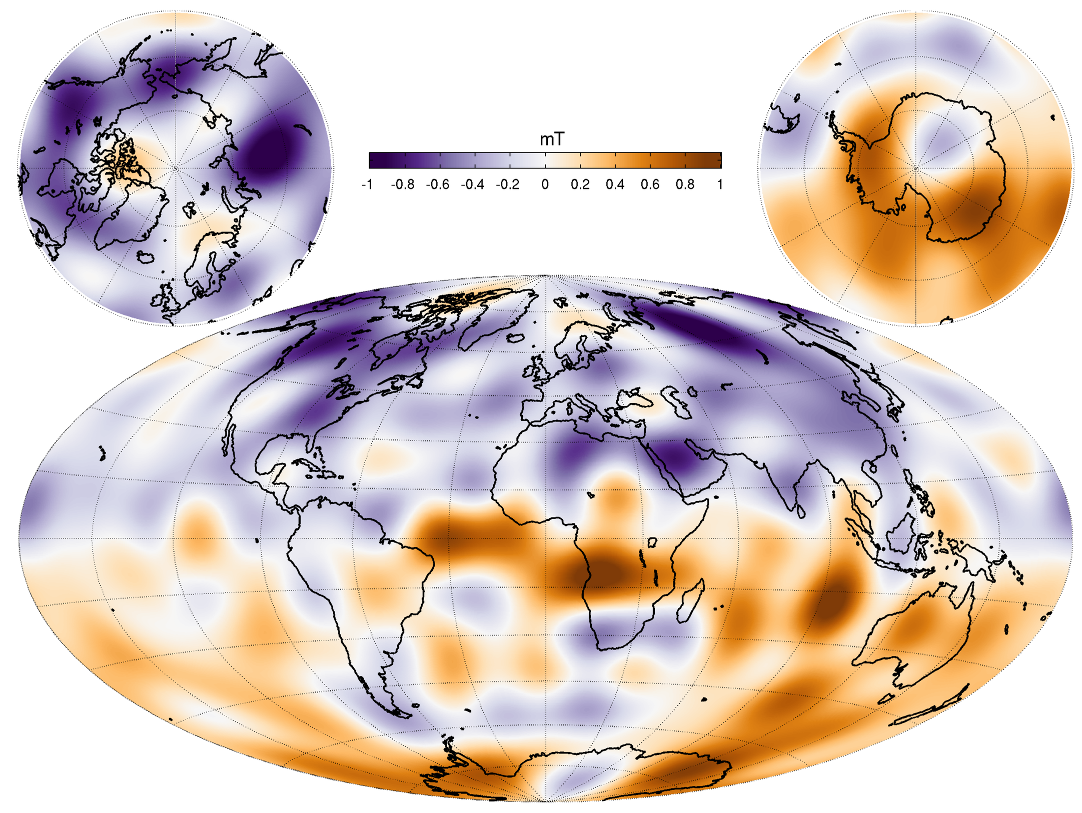

Fig. 7: Above: Radial magnetic field, to degree $n = 14$, plotted at the core surface in 2014.5.

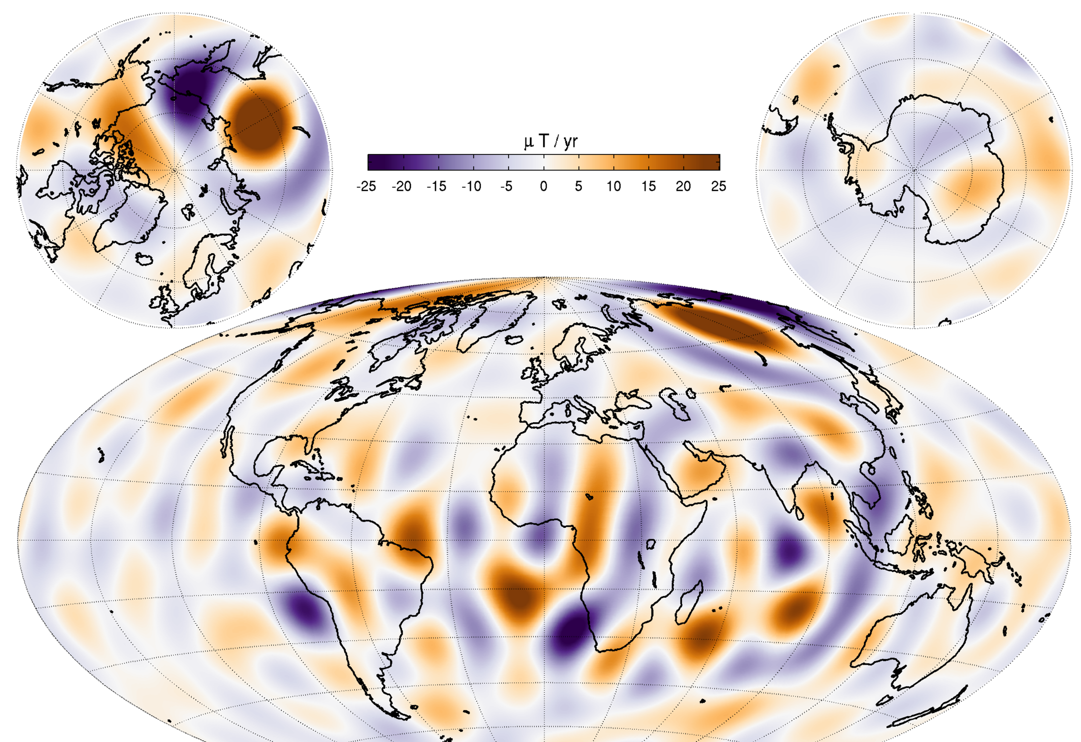

Fig. 8: Above: Time derivative of the radial magnetic field, to degree $n = 15$, plotted at the core surface in 2014.5.

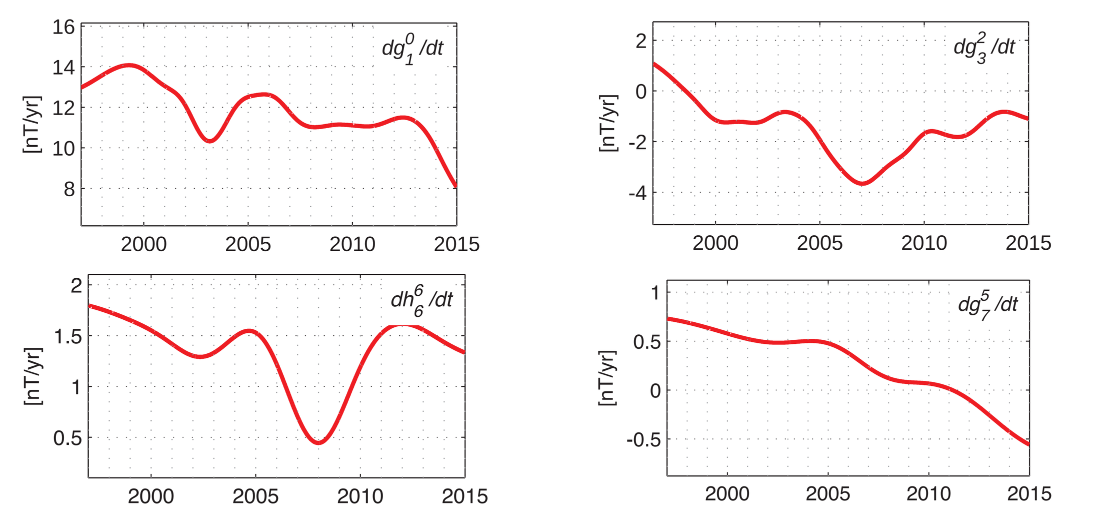

Fig. 9: Above: Time derivative (secular variation) of example spherical harmonic coefficients of the internal potential vs time.

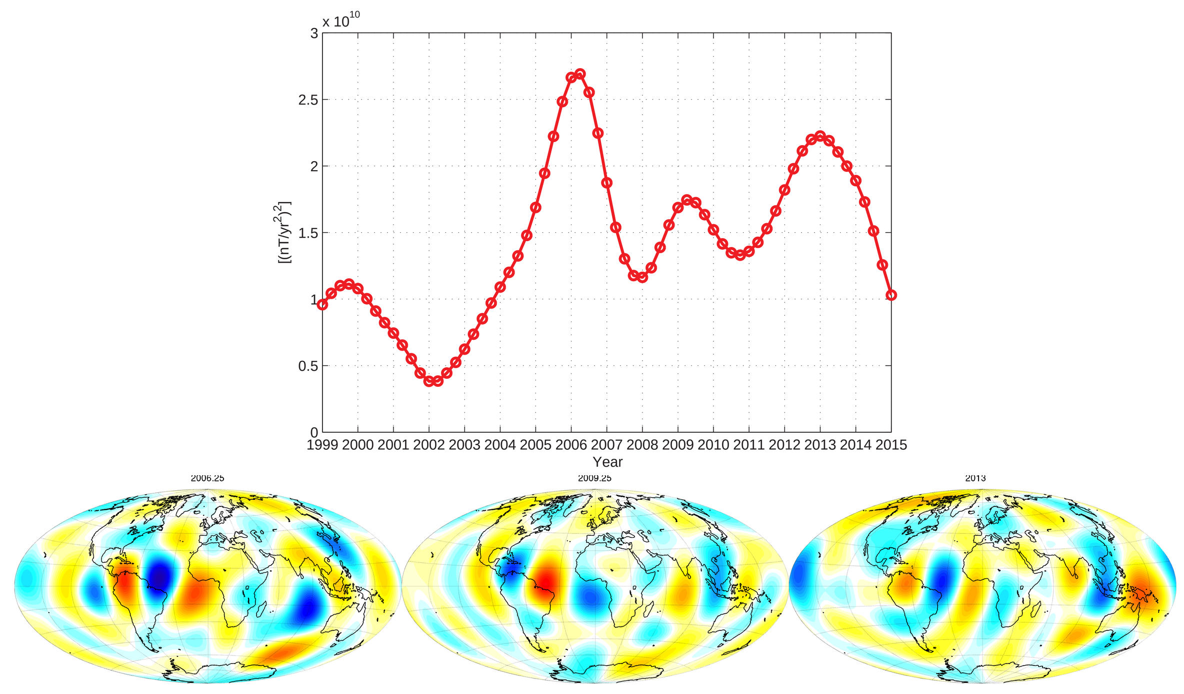

Fig.10: Top: Time evolution of norm (to deg n=8) of second time derivative of the field (SA) at core surface with pulses of activity. Below: Maps of radial SA (to deg n=8) during times of SA pulses. Note the sign changes at low latitudes in the Atlantic sector.

Conclusions and outlook

- ESA's Swarm satellite trio has been successfully launched and all three satellites are already providing high quality magnetic data for core field studies
- CHAOS-4plus: a time-dependent geomagnetic field model spanning 1999-2014, uses latest Swarm data
- Consistently accounts for data from 6 satellites: Ørsted, CHAMP, SAC-C, and *Swarm-A, B, C*
- Provides stable images of field and its rate of change in 2014 at the core surface
- Localized acceleration episodes: 2006, 2009, 2013?
- Moving forward new techniques needed to fully exploit *Swarm* data e.g.
  - Use of gradient estimates
  - Covariance & bias due to unmodelled signals
- Expect further improvements in Swarm data calibration in the upcoming months

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